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2 **Examining the spatiotemporal disruption to gaze when using a myoelectric prosthetic**

3 **hand**

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23 **Abstract**

24 The aim of this study was to provide a detailed account of the spatial and temporal
25 disruptions to eye-hand coordination when using a prosthetic hand during a sequential fine
26 motor skill. Twenty-one abled-bodied participants performed 15 trials of the ‘picking up
27 coins’ task derived from the Southampton Hand Assessment Procedure (SHAP) with their
28 anatomic hand and with a prosthesis simulator while wearing eye-tracking equipment. Gaze
29 behaviour results revealed that when using the prosthesis, performance detriments were
30 accompanied by significantly greater hand-focused gaze and a significantly longer time to
31 disengage gaze from manipulations to plan upcoming movements. Our findings highlight key
32 metrics that distinguish disruptions to eye-hand coordination that might have implications for
33 the training of prosthesis use.

34 *Keywords:* eye-hand coordination, prosthesis, amputee, visuomotor control, visual attention

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44 **1. Introduction**

45 The human hand represents a prehensile tool that enables us to interact with our environment
46 through a complex repertoire of sophisticated movements (Clement, Bugler, & Oliver, 2011).
47 The sensory structure of the hand contains a high density of mechanoreceptors that provide
48 haptic feedback regarding the geometric properties of a grasped object (Brand, 1985),
49 enabling fine control of grip forces and the detection of grip slippage (Cohen, 1999). It is
50 therefore no surprise that the loss of a hand and its subsequent disruption to eye-hand
51 coordination can significantly impact the ease with which day-to-day activities are performed
52 following the introduction of a myoelectric prosthesis (Pasluosta, Tims, & Chiu, 2009). As
53 well as managing the significant reductions in degrees of freedom, proprioception and haptic
54 feedback, the difficult challenge for users is to re-learn how to control their new ‘hand’ with
55 different muscle groups (via electrodes) and neural pathways from those used in the
56 anatomical hand (Bouwsema, Kyberd, Hill, van der Sluis, & Bongers, 2012). This process
57 demands high levels of attention during grasping activities, leading to a high conscious
58 burden for users (Carrozza et al., 2001) and high rejection rates of these types of devices
59 (Williams & Walter, 2015).

60 To understand the challenges that an amputee faces when attempting to relearn these
61 skills it is worth examining the role that vision plays in the development of eye-hand
62 coordination. Evidence suggests that newborn human infants attempt to view their hands
63 when reaching for objects in the early stages of development (van der Meer, van der Weel, &
64 Lee, 1995; van der Meer, 1997) although human adults rarely fixate the hand when reaching
65 and grasping (Johansson, Westling, Bäckström, & Flanagan, 2001; Land, Mennie, & Rusted,
66 1999; Pelz & Canosa, 2001). Burnod et al. (1999) proposed that this reliance on vision to
67 monitor the moving hand (as seen in infants) represents an important stage in learning
68 visuomotor transformations in the context of reaching and grasping. By closing the visual-

69 manual loop, initial sensorimotor mapping rules between commands and movements and
70 between vision and proprioception are explored and learned (von Hofsten, 2004). After these
71 rules have been established typical reaching and grasping involves the eyes leading the hands,
72 playing a proactive and sequential role in supporting the performance of tasks of daily living.
73 For example, Land et al. (1999) found that the eyes often move onto a subsequent ‘to-be-
74 grasped’ object about half a second before manipulation of a current object is complete. In
75 effect, they are able to disengage visual attention from action as soon as another sense (i.e.,
76 proprioception) can take over from it. Therefore, the development of eye-hand coordination is
77 characterised by an early reliance on visual information to guide hand movements and object
78 manipulations that relinquishes to more proprioceptive modes of control as the eyes start to
79 precede hand movements and coordination develops (Sailer, Flanagan, & Johansson, 2005).

80 Therefore, when an individual suffers an amputation and is fitted with a hand
81 prosthesis it is likely that the previously acquired sensorimotor mapping rules related to the
82 control of their anatomical hand are lost or become redundant. Consequently, an amputee
83 may be forced to reinvest in primitive control processes resulting in a corresponding reliance
84 on vision to monitor and control prosthetic hand movements. Vision then reverts from a
85 feedforward to a feedback resource (Sailer et al., 2005) and is used to supervise on-going
86 actions as opposed to planning future actions ahead of time. In fact, previous research has
87 found support for this disruption to ‘normal’ eye-hand coordination in studies exploring
88 skilled tool use and prosthetic hand use.

89 For example, in laparoscopic surgery tasks - a skill that is similar to prosthesis use as
90 it requires the manipulation of a ‘tool’ that is external to the body and has limited
91 proprioceptive feedback – researchers have shown that novice surgeons spend more time
92 fixating the surgical tool rather than to-be-grasped objects (Vine, Masters, McGrath, Bright,
93 & Wilson, 2012; Wilson et al., 2010). In contrast, experienced surgeons use a “target-

94 focused” gaze strategy where they focus on the object that needs to be manipulated (Wilson
95 et al., 2010). In prosthetic hand use, Sobuh et al. (2014) highlighted key differences in gaze
96 strategies of individuals when using their anatomic hand compared to when using a prosthetic
97 hand. In their study, anatomically intact participants devoted more of their attention to the
98 hand and grasping critical areas when using a prosthetic simulator than when using their
99 intact hand during a discrete carton-pouring task. Additionally, they made more saccadic
100 transitions between areas of interest when using the prosthesis simulator, reflecting more
101 erratic and novice-like gaze behaviour (Hermens, Flin, & Ahmed, 2013). In a study
102 examining the visuomotor behaviours of experienced upper limb prosthesis users, Bouwsema
103 et al. (2012) revealed that although users focused their gaze on the object to be grasped for
104 the majority of the task (“target-focused”), there was still a tendency to switch between the
105 object and the hand during performance. The results of these studies indicate that increased
106 visual dependency in the early development of tool use reflects compensatory strategies in
107 the absence of proprioception.

108 Whilst research thus far has distinguished differences in gaze behaviour between
109 anatomic and prosthetic hand use (Bouwsema et al., 2012; Sobuh et al., 2014), findings have
110 been limited to reporting overall percentages of fixations dedicated to each individual area of
111 interest (AOI) and to assessing the number of transitions between these spatial locations.
112 These measures, although revealing, do not examine the temporal coupling between vision
113 and action and therefore ignore the vital role that vision plays in planning, guiding and
114 controlling movements in sequential movements typical of activities of daily living.
115 Furthermore, as these studies have been limited to single object reach and grasp activities it is
116 unknown how visuomotor control is utilised during more difficult tasks that require greater
117 levels of fine motor control. Therefore, to further understand the disruption to eye-hand
118 coordination in prosthetic hand use then more detailed information is needed regarding the

119 coupling of hand and eye movements as they support successful task execution in actions
120 requiring high levels of dexterity.

121 The aim of the present study was therefore to explore the disruption to eye-hand
122 coordination during prosthetic hand use in a sequential task requiring fine motor control. We
123 hypothesized that participants' performance would be significantly slower compared to when
124 using their anatomical hand. We further hypothesised that these impairments would be
125 underpinned by two specific disruptions to the spatial allocation and temporal orientation of
126 visual attention. First, we predicted that when using the hand prosthesis participants would be
127 significantly more hand-focused throughout all phases of the task, reflecting more fixations
128 dedicated to guiding the hand or objects being manipulated by the hand (Bouwsema et al.,
129 2012; Sobuh et al., 2014). Second, we predicted that reductions in haptic feedback when
130 using a prosthesis would prevent the disengagement of gaze during initial object
131 manipulation previously shown in able-bodied participants (Land et al., 1999), resulting in a
132 significant delay in the time taken to shift gaze away from the manipulation and onto the next
133 task component. Finally, we predicted that disruptions in the spatial and temporal allocation
134 of gaze would be significant predictors of task performance.

135 **2. Materials and methods**

136 *2.1 Participants*

137 Twenty-one participants (13 males and 8 females; age $M = 25.32$, $SD = 5.05$ yrs.)
138 volunteered to participate in the study. Sample size estimates were based on previous
139 literature examining skilled and novice gaze behaviour during tool use that had shown
140 significant performance effects (Wilson et al., 2010; Wilson, et al., 2011). All participants
141 were able-bodied, had normal or corrected vision and had no prior experience with a
142 prosthesis simulator. All participants reported to be right handed as indicated by The

143 Edinburgh Handedness Inventory (Oldfield, 1971). The study was approved by the local
144 ethics committee and written informed consent was given prior to testing.

145 *2.2 Apparatus*

146 *2.2.1 Prosthetic hand*

147 The prosthesis used in this study was the Bebionic™ (Steeper) fully articulating
148 myoelectric hand with multiple pre-programmed grip positions. In order to fit able-bodied
149 participants, the hand was attached to the end of a carbon fibre trough in which participants'
150 forearm and fist was positioned and fastened with Velcro straps (Fig 1). Like most
151 myoelectric hands, this hand is controlled by muscular contractions detected by two
152 electrodes placed on the extensor (extensor carpi radialis) and flexor (flexor carpi radialis)
153 muscles of the forearm. These electrodes (width 18mm x length 27mm) are high in sensitivity
154 (2000-100,000 fold) and range (90-450Hz) and measure electrical changes ($\geq 10\mu\text{V}$) on the
155 skin covering the control muscles. These signals instruct five individual actuators within the
156 hand to provide the desired movements. Activation of the extensors trigger the opening of the
157 hand whereas activation of the flexors trigger the closing of the hand. Although the prosthetic
158 hand can provide 14 selectable grip patterns, the hand was pre-programmed into the 'tripod'
159 grip, as is recommended in the SHAP manual.

160 *2.2.2. The Coin Task*

161 The Southampton Hand Assessment Procedure (SHAP) is a clinically validated hand
162 function test that was developed to assess the effectiveness of upper limb prostheses (Light,
163 Chappell, & Kyberd, 2002). The SHAP is made up of 6 abstract objects and 14 activities of
164 daily living (ADL). For this experiment, we used the *picking up coins* task, which is one of
165 the included ADLs. This sequential task required participants to pick up two 2 pence (2.6cm

166 in diameter) and two 1 pence (2cm in diameter) coins from designated areas on the SHAP
167 board (from right to left) and sequentially drop them into a glass jar located in the centre of
168 the board (Fig 1). Specifically, participants were required to place their hand on the hand mat
169 at the start of each trial, and at a time of their choosing, begin the trial by pressing the button
170 on the timer. Once pressed they were required to sequentially drag each coin to the edge of
171 the table in order to pick them up before dropping them in the jar. Once all coins had been
172 dropped in the jar they were required to re-press the trial timer button to end the trial and
173 replace their hand on the mat. If a coin was dropped during the trial the participant was asked
174 to move on to the next coin while a researcher replaced the coin that was dropped.

175 *2.2.3 Gaze behaviour*

176 Gaze behaviour was measured with an Applied Science Laboratories (ASL; Bedford,
177 MA) Mobile Eye XG gaze registration system that measures eye line of gaze at 30Hz with
178 respect to eye and scene cameras mounted on a pair of glasses. The system consists of a
179 recording device (a modified DVCR) and a laptop (Dell Inspiron 6400) with 'Eye-vision'
180 software installed. A circular cursor, representing 1° of visual angle with a 4.5mm lens,
181 indicating the point of gaze in a video image of the scene (spatial accuracy of $\pm 0.5^\circ$ visual
182 angle; 0.1° precision) was recorded for offline analysis.

183 *2.3 Procedure*

184 Upon arrival, participants were informed of the purpose of the investigation and were
185 provided with a brief introduction to the testing equipment and apparatus. Each participant
186 then read and completed the informed consent. Participants were then sat comfortably at a
187 table, with their elbows resting at approximately 90 degrees to conform to the SHAP task
188 instructions. The eye tracker was fitted and calibrated by asking participants to direct their
189 gaze to nine different points marked within the scene. The task was then explained and a brief

190 demonstration was given before a full practice was allowed. Participants then performed 15
191 trials of the coin task with their right anatomic hand (a total of 60 coins). After a brief rest,
192 participants were then fitted with the prosthesis simulator and were allowed to practice
193 sending open and close signals until the participant could consistently (on at least five
194 consecutive occasions) send these signals when instructed. After one full practice trial of the
195 coin task wearing the prosthetic hand simulator, participants then completed 15 full
196 experimental trials. Gaze behaviour was continuously monitored throughout testing and re-
197 calibrated if necessary (approximately every fifth trial).

198 *2.4 Measures*

199 *2.4.1 Performance*

200 Performance was measured as the time (in seconds) taken to sequentially place all
201 four coins from right to left into the tin. The timer (and thus task) was initiated and
202 terminated via a button press by the participant.

203 *2.4.2 Gaze data*

204 Video data from the Mobile Eye were analysed offline using Quiet Eye Solutions
205 software (Quiet Eye Solutions Inc.) which provides detailed frame-by-frame coding of the
206 motor action and the gaze behaviour of the performer, creating “vision in action” data
207 (Vickers, 2007). At each frame, the gaze was determined to be lying within one AOI, defined
208 in Fig 1. On occasions where AOIs overlapped, priority was given to the AOI that was
209 initially fixated upon so long as the obscuring AOI did not cause the position of this fixation
210 to change. If gaze shifted from its original position following AOI overlap then priority was
211 given to the now obscuring AOI. To further understand the disruptions to gaze throughout the
212 different phases of the task, the task was broken down into six distinct movement phases;

213 button press 1 (*B1*), coin reach (*Reach*), coin drag (*Drag*), Lift and drop (*Lift/drop*), button
214 press 2 (*B2*) and hand return (*Hand return*). Fig 2 gives a visual representation of each task
215 phase, defining their given onset and offset. Fixations made outside of AOIs were
216 collectively labelled as “Other”. Consistent with previous research (e.g., Vickers & Williams,
217 2007; Wilson, Vine, & Wood, 2009) gaze analysis was performed on a subset of data (every
218 third trial) resulting in a total of 5 trials and 20 coin pickups per participant.

219 *2.4.3 Target Locking Strategy*

220 To provide an indication of efficient gaze control, we adopted a “target locking
221 strategy” (TLS), previously used by Wilson et al. (2010). This measure is computed by
222 subtracting the percentage of time spent fixating the “tool” (or “hand” for the present study)
223 from the time spent fixating the target. Thus, a more positive score reflects more time fixating
224 on targets whereas a negative score reflects more time spent fixating the hand. A score of ‘0’
225 reflects equal time spent fixating the hand and targets and represents a ‘switching strategy’.
226 For the present study, fixations made towards the hand, or objects being manipulated by the
227 hand, were considered “hand-focused”, whereas fixations towards the target object of a
228 current movement phase were considered “target-focused”. For example, fixations towards
229 the coin would be considered “target-focused” during the ‘reach’ phase, but considered
230 “hand-focused” during the ‘drag’ and ‘lift and drop’ phases when being manipulated by the
231 hand. Interrater reliability from a sample of 50 coins revealed 94% agreement.

232 *2.4.4 Gaze shifting*

233 In order to examine the temporal sequencing of gaze behaviour we measured the time
234 (in milliseconds) that the eye was ahead of the hand movement. To do this we calculated the
235 time taken to shift attention towards the next task component following the completion of the
236 previous task component. If gaze was shifted to the next target before completion of the

237 previous task phase, then a negative time was recorded, indicating that gaze was ahead of the
238 hand. A positive time reflected the extent to which the eye was behind the action of the hand.
239 This measure therefore quantified the time taken to shift gaze to coin 1 following B1
240 completion (button to coin), to coin 2, 3 and 4 following Lift and drop completion (jar to
241 coin), to the jar following Drag completion (coin to jar), and to the button at the initiation of
242 B2 (jar to button). The mean time to shift was then calculated for each phase separately.
243 Interrater reliability from a sample of 50 coins revealed 98% agreement.

244 *2.5 Statistical Analysis*

245 All data were first subject to outlier analysis, in which data falling outside 2.2 times
246 the corresponding upper and lower interquartile range were removed from further analysis
247 (Hoaglin & Iglewicz, 1987). A Wilcoxon signed-rank test was used to compare the mean
248 performance time between anatomic and prosthetic hand conditions. For overall AOI fixation
249 percentages, a 2 x 6 repeated measures ANOVA was performed with hand condition
250 (anatomic vs prosthetic) as the between-subjects factor and AOI (Hand, Button, Coin, Jar,
251 Hand mat, Other) as the within-subjects factor. For TLS, a 2 x 6 repeated measures ANOVA
252 was also performed with hand condition as the between-subject factor and task phase (B1,
253 Reach, Drag, Lift and drop, B2, Hand return) as the within-subject factor. For the gaze
254 shifting measure a 2 x 4 ANOVA was performed with hand condition as the between-subject
255 factor and transition between task phases (button to coin, jar to coin, coin to jar, jar to button)
256 as the within-subject factor. Finally, linear regression analysis was then carried out to explore
257 if disruptions in TLS of gaze shifting were significant predictors of performance.

258 Where sphericity was violated, Greenhouse-Geisser corrections were applied. Effect
259 sizes were calculated using partial eta squared (η_p^2) for omnibus comparisons and Cohen's *d*
260 for pairwise comparisons (Cohen, 2013).

261 3. Results

262 3.1 Performance

263 Results from the Wilcoxon signed-ranks test showed that participants performed
264 significantly slower, $Z = -4.02$, $p < .001$, $d = -5.51$, when using the prosthesis simulator ($M =$
265 51.97 , $SD = 17.27$ seconds) compared to when using their anatomic hand ($M = 4.73$, $SD =$
266 0.15 seconds).

267 3.2 Total AOI Fixation %

268 No significant main effect was found for hand condition, $F(1, 19) = 0.32$, $p = .577$, η_p^2
269 $= 0.02$, but there was a significant main effect of AOI, $F(5, 95) = 440.85$, $p < .001$, $\eta_p^2 = 0.96$.
270 There was also a significant hand condition x AOI interaction, $F(3.25, 61.83) = 296.87$, $p <$
271 $.001$, $\eta_p^2 = 0.94$. Follow up paired samples t -tests between hand conditions revealed that
272 when wearing the prosthesis, participants dedicated significantly greater visual attention to
273 the hand ($p < .001$), and coin ($p < .001$), and significantly less visual attention to the button,
274 ($p < .001$) and jar, ($p < .001$), compared to when using their anatomical hand (Fig. 3).

275 Post hoc repeated measures ANOVAs within each hand condition revealed a
276 significant difference, $F(2.63, 52.74) = 207.31$, $p < .001$, $\eta_p^2 = 0.91$, in overall percentage of
277 fixation percentage dedicated to each AOI in the anatomic hand condition. Pairwise
278 comparisons revealed that participants dedicated a significantly higher percentage of fixations
279 towards the button than all other AOIs ($ps < .001$) and significantly higher percentage to the
280 coin and jar compared to the hand, hand mat and other AOIs ($ps < .001$). Within the
281 prosthetic hand condition, a significant difference, $F(3.17, 60.14) = 659.06$, $p < .001$, $\eta_p^2 =$
282 0.97 , revealed that participants dedicated a significantly higher percentage of fixations
283 towards the coin compared to all other AOIs ($ps < .001$; Fig 3).

284 3.3 Target locking strategy

285 Significant main effects for hand condition, $F(1, 13) = 507.59, p < .001, \eta_p^2 = 0.98,$
 286 and movement phase, $F(5, 65) = 253.37, p < .001, \eta_p^2 = 0.95,$ were found for TLS. Results
 287 also indicated a significant condition x movement phase interaction, $F(5, 65) = 115.11, p <$
 288 $.001, \eta_p^2 = 0.89.$ Follow-up paired samples t -tests between hand conditions revealed that
 289 when wearing the prosthesis, participants exhibited significantly lower target-locking
 290 strategies throughout all phases of the task ($ps < .001$) compared to anatomic hand use (Fig
 291 4).

292 Post hoc repeated measures ANOVAs within each hand condition revealed a
 293 significant difference, $F(2.38, 36.91) = 83.71, p < .001, \eta_p^2 = 0.84,$ in TLS score across task
 294 phases in the anatomic hand condition. Pairwise comparisons revealed that B1 and Lift and
 295 Drop phases had significantly higher TLS compared to the Reach phase ($ps < .01$).
 296 Furthermore, the Drag phase scored significantly lower TLS compared to all other task
 297 phases ($ps < .001$). For the prosthetic hand condition a significant difference, $F(2.94, 52.82)$
 298 $= 266.24, p < .001, \eta_p^2 = 0.94,$ was found across all task phases. Pairwise comparisons
 299 revealed that participants scored significantly lower TLS in the Drag task phase compared to
 300 all other phases ($ps < .001$; Fig 4).

301 3.4 Gaze shifting

302 A significant main effect of hand condition, $F(1, 12) = 165.67, p < .001, \eta_p^2 = 0.93,$
 303 and movement phase, $F(3, 36) = , p < .01, \eta_p^2 = 0.39,$ was found for the time to shift gaze.
 304 Results also indicated a significant hand condition x movement phase interaction, $F(3, 36) =$
 305 $45.73, p < .001, \eta_p^2 = 0.79.$ Follow up paired samples t -tests between hand conditions
 306 revealed that when wearing the prosthesis, participants took significantly longer to shift gaze
 307 throughout every movement phase of the task compared to their anatomic hand (Fig 5).

308

309 Post hoc repeated measures ANOVAs within each hand condition revealed a
310 significant difference, $F(3, 45) = 20.47, p < .001, \eta_p^2 = 0.58$, in time to shift gaze across task
311 phases in the anatomic hand condition. Pairwise comparisons revealed that participants
312 shifted gaze significantly earlier from the coin to the jar compared to the button to coin ($p <$
313 $.01$), jar to coin and jar to button ($ps < .001$). Participants also shifted gaze significantly
314 earlier from the button to coin than from the jar to coin ($p < .01$). No other significant
315 differences were found ($ps > .30$). For the prosthetic hand condition a significant difference,
316 $F(3, 51) = 29.64, p < .001, \eta_p^2 = 0.64$, revealed that participants took significantly longer to
317 shift gaze from coin to jar than from any other movement phase ($ps < .01$). Participants also
318 took significantly longer to shift gaze from button to coin than from jar to button ($p < .001$).
319 No further significant differences were found ($ps = 1.00$; Fig 5).

320 3.5 Regression Analysis

321 Linear regression analysis revealed that the measure of gaze shifting was a significant
322 predictor, $R^2 = 0.32, b = 0.56, p = 0.01$, of performance in the coin task. TLS score did not
323 significantly predict task performance, $R^2 = 0.16, b = -0.40, p = 0.08$.

324 4. Discussion

325 This is the first study to explore the spatiotemporal disruption to eye-hand
326 coordination when using a myoelectric prosthetic hand in a sequential fine motor task. We
327 predicted that when using a prosthetic hand simulator, participants would exhibit significantly
328 poorer performance and that this disruption would be underpinned by disruptions to the
329 spatiotemporal allocation of gaze throughout the task. Confirming our predictions, the use of
330 the prosthesis caused a significant decrease in performance, with the coin task taking on

331 average 10 times longer when participants used the prosthetic hand compared to their
332 anatomical hand. Furthermore, these performance disruptions were underpinned by
333 disruptions to the gaze behaviour of participants.

334 For the spatial allocation of gaze, data from overall AOI fixation percentages revealed
335 that when using the prosthesis participants dedicated significantly more fixations to the hand
336 and coin. Conversely, when using their anatomical hand, participants dedicated significantly
337 more fixations to the button, jar, and hand mat. Whilst this data provides an overall picture of
338 the spatial allocation of gaze, as reported in previous studies (Bouwsema et al., 2012; Sobuh
339 et al., 2014), there are issues that arise when interpreting such data. For example, Figure 6
340 displays model gaze sequences taken from an anatomic and prosthesis trial, indicating the
341 spatial and temporal allocation of gaze. Despite the coin receiving a considerable amount of
342 fixations in both conditions, these fixations occur mainly during the Reaching phase for the
343 anatomic condition (target-focused), and mainly during the Drag phase during the prosthesis
344 condition (hand-focused). Thus, analysing the spatial allocation of gaze without considering
345 the task-specific temporal relevance of such fixations may result in a degree of
346 misinterpretation.

347 Results from our TLS measure indicated that participants directed significantly more
348 visual attention to the hand (lower TLS) throughout every movement phase of the task whilst
349 wearing the prosthesis (Fig 4). Specifically, participants scored significantly lower TLS
350 during the 'Reach' and 'Lift and Drop' phases. While both phases still received a positive
351 TLS (37% for 'reach' and 23% for 'lift and drop'), this still reflects greater hand-focused
352 gaze compared to anatomic hand use but is more reflective of a gaze 'switching' strategy
353 (TLS of 0%) previously reported in similar studies (Bouwsema et al., 2012; Sobuh et al.,
354 2014). There are two possible explanations for this switching strategy. It could be that
355 participants switched their attention between the hand and the target during the 'Reach' and

356 'Lift and Drop' phases to monitor the relationship between motor commands, movements and
357 proprioception in an attempt to develop 'new' sensory mapping rules and better hand control
358 (Sailer et al., 2005). Alternatively, it could be that participants increased their visual attention
359 to the hand when lifting and dropping the coin due to the uncertainty in grip security that
360 hand prosthesis users experience (Chadwell, Kenney, Thies, Galpin, & Head, 2016; Pylatiuk,
361 Schulz, & Döderlein, 2007) due to deficits in haptic feedback that is essential for skilled and
362 dextrous object manipulation (Jenmalm, Dahlstedt, & Johansson, 2000). Finally, participants
363 were almost exclusively hand-focused during the 'Drag' phase of the coin task. While this is
364 also likely to reflect visual dependency in the absence of haptic feedback, this dependency is
365 further compounded by the precision needed when manipulating the coin to hang over the
366 edge of the table and the associated performance cost of dropping the coin on the floor. This
367 is evident from the finding that the 'Drag' phase also resulted in significantly lower TLS than
368 the other task phases during the anatomic hand condition. These findings replicate and extend
369 those of Bouwsema et al. (2012), and Sobuh et al. (2014), to a sequential task requiring
370 greater levels of dexterity and fine motor control.

371 In terms of the temporal orientation of gaze our data show that when using their
372 anatomic hand participants were able to fixate upcoming targets approximately 45ms before
373 manipulation of the previous object was complete, aligning with previous research that has
374 showed how haptic information enables the disengagement of gaze (Land, 2009). The
375 introduction of a prosthesis resulted in a substantial delay (mean of 313ms) in the time to
376 shift gaze onto the next target in the movement phase following completion of the previous
377 movement phase. This again aligns with the findings of Sobuh et al. (2014) and highlights
378 how reductions in haptic feedback, responsible for encoding information regarding the nature
379 of a manipulation, induce grip uncertainty and visual dependence. However, as these delays
380 in gaze shifting also occurred in the absence of a manipulation, they also reflect the need to

381 visually monitor prosthetic hand movements during the early stages of learning to develop
382 novel sensory mapping rules (Sailer et al., 2005). Importantly, regression analysis highlighted
383 that our gaze shifting measure was a significant predictor of prosthesis task performance.
384 This supports the notion that skilled performance is as dependent on the correct allocation of
385 gaze in time as in space (Tatler, Hayhoe, Land, & Ballard, 2011), and suggests that future
386 research should account for the temporal coupling between hand and eye movements.

387 Taken together, our results suggest that the disruption to eye-hand coordination when
388 using a prosthesis is characterised by increased hand-focused gaze strategies and a reduced
389 ability to disengage gaze from object manipulations. This prevents the planning of future
390 task-related movements ahead of time leading to a dependency on the online conscious
391 control of the hand and reduced performance. This type of movement control seems
392 indicative of the exploratory or cognitive stage of learning (Fitts & Posner, 1967) where
393 learners explicitly test hypotheses and declarative knowledge concerning movement rules is
394 formulated, placing high demands on cognitive resources (Masters & Maxwell, 2008).
395 Interestingly, this interpretation also resonates with the subjective experiences of prosthetic
396 hand users who report that the high cognitive burden is a primary reason for device
397 dissatisfaction and rejection (Cordella et al., 2016).

398 A possible intervention that has been shown to reduce this cognitive burden during
399 the early stages of learning is implicit motor learning. Implicit motor learning techniques are
400 designed to prevent the build-up of explicit knowledge during skill acquisition resulting in a
401 low conscious awareness of what is being learned about the execution of this skill. As a
402 consequence, this form of learning has been shown to be less resource intensive than explicit
403 techniques (i.e., movement-related verbal instructions), whilst also producing more resilient
404 performance under high levels of fatigue (Masters, Poolton, & Maxwell, 2008) and task
405 difficulty (Maxwell, Masters, & Eves, 2003). Given that prosthetic hand rejection rates have

406 also been attributed to difficulty and fatigue (Cordella et al., 2016; Pylatiuk et al., 2007),
407 avoiding the involvement of explicit movement processing via implicit learning may offer
408 some clinical benefit for prosthetic hand users. Future research should therefore seek to
409 confirm the level of conscious movement processing during initial prosthetic use and explore
410 the efficacy of implicit learning techniques designed to reduce the cognitive burden
411 associated with this early stage of the rehabilitation process.

412 Another interesting avenue for future research includes exploring the effectiveness of
413 gaze training interventions, which have also been shown to be a form of implicit motor
414 learning (Vine, Moore, Cooke, Ring, & Wilson, 2013). Training novices to adopt expert like
415 gaze behaviours has been shown to expedite the learning process in a multitude of sport skills
416 (Wilson, Causer, & Vickers, 2015) and to facilitate eye-hand coordination in children with
417 movement disorders (Miles, Wood, Vine, Vickers, & Wilson, 2017; Wood et al., 2017). It is
418 noteworthy that this type of intervention has also been shown to be successful for training
419 novices in laparoscopic surgical skills; a fine motor skill that also requires the use of a tool
420 with diminished proprioceptive feedback (Vine et al., 2012; Wilson et al., 2011). Thus, by
421 adopting expert-like gaze behaviours, prosthesis users may be able to bypass the explicit
422 processes that accompany the sensory-mapping stage of learning and reduce the attentional
423 demands associated with this complex movement. Future research should test the efficacy of
424 gaze training interventions for prosthetic hand users.

425 Despite these interesting findings, several limitations of the study should be
426 addressed. First, although we have highlighted significant spatial and temporal disruptions to
427 gaze for anatomically intact users of a prosthesis simulator, it is still unclear if these findings
428 are representative of early prosthesis use in upper-limb amputees. Interestingly, Sobuh et al.
429 (2014) found similarities between the gaze behaviours exhibited by intact users of a simulator
430 and amputee subjects - although the task used had relatively few movement phases and no

431 examination of the temporal disruption to gaze was reported. Therefore, future research
432 should examine if these findings transfer to clinical populations. Second, the present study is
433 also potentially limited by the fixed rather counterbalanced order of hand conditions.
434 However, such is the difference in control mechanisms when using the prosthetic hand
435 (compared to the anatomic), that any gains from practicing the task with the anatomic hand
436 would have been irrelevant in facilitating prosthetic hand control. Finally, whilst our gaze
437 shifting measure provided some temporal detail regarding the allocation of gaze during the
438 early part of each task phase, more fine-grained analyses could be explored in future research
439 by quantifying the number of look-ahead and look-back fixations within task phases
440 (Chadwell et al., 2016). Despite this, our relatively simple measure of the temporal allocation
441 of gaze was sensitive enough to be a significant predictor of task performance.

442 To conclude, the present study clearly shows that the early stages of prosthetic hand
443 use are characterised by a severe breakdown in the spatial and temporal coupling between
444 vision and action in this task requiring fine motor control. While great strides are being made
445 in the technological advancements of prosthesis design and manufacture, it is clear that
446 empirical studies examining the optimal method for teaching users to interact with this
447 technology are still in their infancy. By increasing our understanding of the specific
448 mechanisms behind the disruption to eye-hand coordination we have highlighted key metrics
449 that can be used to determine the effectiveness of any intervention designed to re-establish
450 optimal eye-hand coordination in prosthetic hand users.

451

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585

586 **Figures Captions**

587 **Fig 1.** The prosthetic hand simulator (top left), the simulator being worn (bottom left) and a
 588 screenshot from the eye-tracker showing the task environment (right) and the Areas of
 589 Interest (AOIs). The magenta crosshair represents the captured pupil in the Eye-vision
 590 software and the red cursor (located on the coin) represents the participant's point of gaze.

591 **Fig 2.** Action shots taken from the eye-tracker camera for each of the six movement phases,
 592 indicating the onset and offset of each phase throughout the coin task. The magenta crosshair
 593 represents the captured pupil in the Eye-vision software and the red cursor represents the
 594 participant's point of gaze.

595 **Fig 3.** Mean (\pm s.e.m) total percentage of fixations dedicated to each area of interest for each
 596 hand condition.

597 **Fig 4.** Mean (\pm s.e.m) target locking score for the anatomic and prosthetic hand conditions
 598 across the six movement phases.

599 **Fig 5.** Mean (\pm s.e.m) time to shift gaze for the anatomic and prosthetic hand conditions
 600 across the six movement phases. Positive times reflect a gaze shift after completion of a task
 601 phase whereas a negative time reflects a gaze shift before a manipulation has been complete.

602 **Fig 6.** Complete sequence of gaze allocation and task phase events during a single anatomic (top) and
 603 prosthesis (bottom) trial of the coin task. Trials were chosen from participant 7 whose performance
 604 times fell closest to the group means. The top row of each hand condition represents the duration of
 605 each task phase (B1 = Button press 1, R = Reach, D = Drag, L = Lift and Drop, B2 = Button press 2,
 606 H = Hand return). The Button, Coin, Jar, Hand mat, and Other rows indicate when (in relation to task)
 607 gaze was fixated on each of these AOIs. Finally, the bottom two rows indicate whether the fixations
 608 towards these AOIs were deemed as either hand-focused or target-focused.

609